

# Risk modeling using multiple probability distributions for the climate sensitivity

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## Abstract

A major challenge for climate policy is the uncertainty in the climate sensitivity, defined as the equilibrium increase of global mean surface temperature in response to an equivalent doubling of CO<sub>2</sub>. The IPCC has reiterated in all its assessments the judgment that the climate sensitivity is probably between 1.5 and 4.5°C, without ever quantifying the probability that it is outside that range. The vagueness of the range has been a long-standing problem for risk modelers, who need a usable probability density function (PDF) for quantitative risk analysis.

Now, however, the problem is no longer that there is no such PDF, but that there are too many. At least six climate sensitivity PDFs have been published recently, which place from 3% to 30% or more of the distribution over 4.5°C. Honest appraisal makes it clear that we have today little grounds for aggregating these diverse PDFs or choosing among them; thus policy modelers and their constituencies must begin to work with multiple PDFs, and to grapple with the consequences of such multi-dimensional uncertainty.

In this poster we present a practical way of viewing multiple PDFs and their numerical characteristics, using a simple, spreadsheet-based tool with a database of published climate sensitivity PDFs. Then, using a selection from the database, we show how multiple PDFs can be used in probabilistic risk models to address three different policy-relevant questions: (1) the implied equilibrium temperature of a given level of radiative forcing (in Wm<sup>-2</sup> or CO<sub>2</sub>-equivalent); (2) the implied equilibrium temperature of a specific CO<sub>2</sub> concentration given uncertainty in non-CO<sub>2</sub> forcing; and (3) the implied equilibrium temperature of a specific increase in radiative forcing, given uncertainty in current net radiative forcing.

Although this presentation focuses on examples based on global policy questions, the methods presented are of practical use for a much wider range of climate risk models, as the uncertainty in the climate sensitivity is a major component of uncertainty in all models linking emissions scenarios to impacts. We conclude with an example of how, combined with a simple impact model for potential species extinctions, multiple climate sensitivity PDFs can be used in models at a variety of scales to evaluate the extinction risks of various policy scenarios.

## Introducing CSUW 1.0: The Climate Sensitivity Uncertainty Workbook

### A tool for comparing climate sensitivity PDFs and facilitating their use in risk models

- Spreadsheet based tool to present multiple climate sensitivity PDFs for comparison and use in risk modeling
- Displays PDFs and CDFs (cumulative density functions) in graphic and tabular form
- Includes published (this version) and user-defined (next version) PDFs and CDFs as columns which can be cut-and-pasted into other risk models
- Available from Paul Baer ([baer@stanford.edu](mailto:baer@stanford.edu))

Current version includes ten climate sensitivity PDFs, as shown in Figure 1 and Table 1.

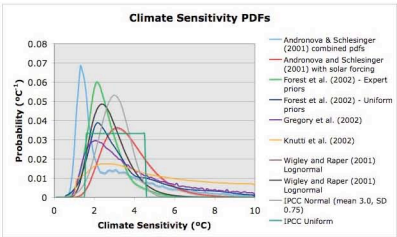


Figure 1. Graphical view of 10 climate sensitivity PDFs included in Version 1.0 of CSUW.

PDF Description	Pct > 2	Pct > 2.5	Pct > 3	Pct > 4	Pct > 4.5	Pct > 5
1 Andreanova & Schlesinger (2001) combined pdfs	49%	41%	35%	22%	18%	14%
2 Andreanova and Schlesinger (2001) with solar forcing	56%	64%	67%	34%	22%	14%
3 Forest et al. (2002) - Expert priors	70%	42%	23%	8%	3%	2%
4 Forest et al. (2002) - Uniform priors	80%	61%	47%	25%	24%	19%
5 Gregory et al. (2002)	79%	65%	53%	35%	29%	24%
6 Knutti et al. (2002)	88%	79%	70%	55%	49%	42%
7 Murphy et al. (2004) weighted PDF	99%	93%	73%	27%	15%	9%
8 Wigley and Raper (2001) lognormal based on IPCC	79%	53%	34%	10%	5%	3%
9 Normal based on IPCC, Mean 3.0°C, SD 0.75°C	91%	75%	51%	10%	3%	1%
10 Uniform based on IPCC	94%	67%	51%	17%	1%	0%
Min	49%	41%	23%	8%	1%	0%
Median	82%	66%	51%	25%	16%	11%
Mean	81%	66%	50%	25%	17%	13%
Max	99%	93%	73%	55%	49%	42%

Table 1: Summary descriptions of 10 climate sensitivity PDFs, showing the fraction of the distributions that are below or above particular threshold values of interest. PDFs highlighted in yellow are used in subsequent analyses.

## Simple risk models included in CSUW 1.0:

### Likelihood for different PDFs of exceeding given temperature thresholds at equilibrium, for arbitrary stabilization levels of net forcing (in CO<sub>2</sub>-equivalent)

- Simple formula linking net forcing to equilibrium temperature does not require Monte Carlo modeling.
- Table 2 below is summary created by hand from 7 individual tables for different stabilization levels, using six representative PDFs.

ppm CO <sub>2</sub> -eq	2°	2.5°	3°	4°	5°
350	1-9%	1-4%	0-1%	0%	0%
400	8-33%	1-16%	0-10%	0-4%	0-1%
450	26-78%	10-42%	4-19%	0-10%	0-5%
500	43-96%	24-74%	11-44%	0-16%	0-9%
550	48-99%	40-91%	21-69%	6-25%	0-14%
600	53-99%	44-98%	33-86%	10-41%	0-18%
650	59-99%	48-99%	42-94%	16-58%	6-24%

Table 2: Likelihood of exceeding various temperature thresholds at equilibrium for different levels of stabilization of radiative forcing (in ppm CO<sub>2</sub>-equivalent)

### Inverse calculation showing maximum net radiative forcing (in ppm CO<sub>2</sub>-equivalent) consistent with different probabilities of staying below various temperature thresholds.

- Again, does not require Monte Carlo modeling.
- Table 3 below is summary for using six representative PDFs.

	50%	67%	75%	80%	90%	95%
2°	418-574	401-467	393-449	397-437	355-410	339-399
2.5°	463-689	440-531	428-506	420-490	377-452	356-423
3°	513-826	482-605	467-570	456-548	401-498	374-460
4°	629-1187	579-783	554-724	538-687	453-605	412-544
5°	771-1706	695-1015	705-920	680-862	638-735	455-643

Table 3: CO<sub>2</sub>-equivalent forcing stabilization levels associated with various combinations of temperature thresholds and desired probability of compliance. (Six representative PDFs; see Table 1)

## Robust Conclusions

- A high likelihood (80-90%) of staying below 2°C increase requires stabilization on the order of 400 ppm CO<sub>2</sub>-equivalent.
- Radiative forcing equal to a doubling of CO<sub>2</sub> has a significant likelihood (6-25%) of exceeding a 4°C temperature increase.
- These results are very similar to those reported in other literature that is either in publication [11] or in press [14].

## Using CDFs/PDFs from CSUW in external risk models

### 1. Projecting equilibrium temperature, accounting for uncertainty in non-CO<sub>2</sub> radiative forcing

- Both current value and projected values of net non-CO<sub>2</sub> forcings are highly uncertain.
- Well-mixed GHGs other than CO<sub>2</sub> add about 1.2 Wm<sup>-2</sup> to current forcing (roughly 100 ppm CO<sub>2</sub>-equivalent).
- In addition to anthropogenic aerosols (estimated to equal to -2 Wm<sup>-2</sup> radiative forcing), other forcing agents include black carbon, tropospheric ozone, volcanic gases, changes in solar flux, and changes in land use.

### A. Modeling uncertain future net non-CO<sub>2</sub> forcing

- SRES projections (marker scenarios) of net non-CO<sub>2</sub> radiative forcing in 2100 range from 0.55 Wm<sup>-2</sup> to 2.45 Wm<sup>-2</sup>. While the SRES scenarios do not represent a statistical sample of any process, as an indicative range, they can be represented subjectively by their mean (1.4 Wm<sup>-2</sup>) and standard deviation (0.7 Wm<sup>-2</sup>).
- A more conservative interpretation, following Wigley [20] on the assumption that there will be climate policy, is a mean of 0.75 Wm<sup>-2</sup> and an SD of 0.3 Wm<sup>-2</sup>.
- Using this distribution, with a the same representative selection of 6 PDFs used previously, a simple Monte Carlo model produces the results shown in Table 4 for the probability of staying below a temperature threshold of 2°C.

	350	400	450
A&S	76%	65%	53%
Forest E	87%	64%	46%
Murphy	63%	24%	7%
IPCC uniform	75%	44%	24%
IPCC normal	78%	45%	20%
WSR lognormal	83%	56%	35%
MIN	63%	24%	7%
MED	77%	51%	30%
MEAN	77%	50%	31%
MAX	87%	65%	53%

Table 4: Probability of staying below 2°C above preindustrial temperature for three CO<sub>2</sub> stabilization levels and six climate sensitivity PDFs, non-CO<sub>2</sub> forcings distributed normally with mean 0.75 Wm<sup>-2</sup>, SD 0.3 Wm<sup>-2</sup>.

### B. Modeling uncertain current net non-CO<sub>2</sub> forcing

- Estimates of net current forcing are very uncertain. The IPCC's TAR shows a table with the uncertainty in each component, but advises against simply aggregating the uncertainties.
- In spite of this, the obvious relevance of estimating current net forcing has led several research groups to do exactly that:
  - Hansen and Sato [9] add them up, treating IPCC uncertainty ranges as one-sigma normal error distributions;
  - Boucher and Haywood [3] use a more sophisticated approach, performing a Monte Carlo analysis using different shape PDFs for different forcing agents.
- Knutti et al. [12] use a Bayesian computational method to estimate a PDF for net current forcing.
- These three PDFs are shown in Figure 2 below. Note that both the Boucher and Haywood and Knutti et al. PDFs have been subjectively rendered as normal distributions.
- Using these three PDFs and the same six representative climate sensitivity PDFs in a simple Monte Carlo model, estimating the risk of exceeding the 2.0°C threshold with 1 Wm<sup>-2</sup> additional forcing produces the calculations shown in Table 5.

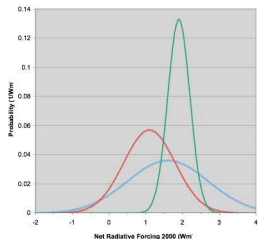


Figure 2: Three PDFs for current net radiative forcing.

Pct<2°C	Boucher and Haywood	Hansen and Sato	Knutti et al.
A&S	76%	67%	57%
Forest E	81%	67%	59%
Murphy	52%	35%	11%
IPCC Uniform	67%	51%	33%
IPCC normal	77%	60%	51%
Wigley	71%	49%	28%
MIN	52%	35%	11%
MED	73%	55%	42%
MEAN	71%	55%	47%
MAX	81%	67%	59%

Table 5: Probability of exceeding 2°C increase above preindustrial temperature for 1 Wm<sup>-2</sup> additional forcing, three PDFs for current net forcing.

## II. Projecting impacts at equilibrium

- The probabilistic output of an equilibrium temperature model using one or more of the climate sensitivity PDFs in CSUW can straightforwardly be used to project risks of impacts of various types.
- In the placeholder example below, equilibrium global temperature increase drives a probabilistic species loss function.
- The curves shown in Figure 3 indicate minimum, median and maximum estimates of the fraction of species lost (shown on the Y axis) for a given equilibrium temperature increase.
- The minimum, median and maximum loss functions are arbitrarily defined as quadratic functions of equilibrium temperature increase. Note that the figures shown below are much lower than the estimates given in [18].
- The functions below were entered into a simple Monte Carlo model in which, in each "run" of the model, a value of equilibrium temperature is estimated first, and then the impact is calculated probabilistically using a triangular distribution using the minimum, median and maximum impact values for that temperature. Table 6 shows the results.

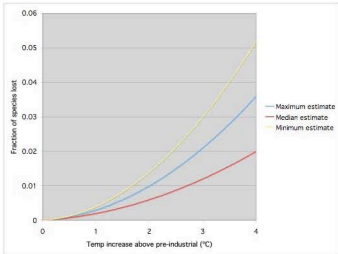


Figure 3. Placeholder example of probabilistic impacts of global mean temperature increase on species loss: min, median and max fraction of species lost at a given temperature increase.

	Median	90th pctl	95th pctl	Maximum
400	0.62-0.63%	0.97-1.00%	1.07-1.11%	1.53-1.83%
450	1.02-1.06%	1.63-1.71%	1.80-1.93%	2.60-3.03%
500	1.46-1.54%	2.34-2.46%	2.63-2.79%	3.93-4.64%
550	1.92-2.01%	3.16-3.29%	3.55-3.73%	5.10-6.32%
600	2.42-2.48%	3.96-4.16%	4.47-4.59%	6.40-8.24%

Table 6: Range of results for placeholder species loss model, showing range of projected percent species loss (median, 90th pctl, 95th pctl, max) for six selected PDFs and five stabilization levels (in ppm CO<sub>2</sub>-equivalent)

## Interpreting the results

- In this particular example, the fairly compressed range for each "entry" (typically less than 5% for all except the maximum value) shows that the estimated impact are not very sensitive to the climate sensitivity PDF or PDFs that are used.
- Using this table, one can give policy recommendations of the following structure:
  - If, using these assumptions, one wishes to have a 90% chance of keeping species loss below 2.5%, atmospheric stabilization has to be no higher than about 500 ppm CO<sub>2</sub>-equivalent.
  - If atmospheric CO<sub>2</sub> concentrations stabilize at 600 ppm CO<sub>2</sub>-equivalent or higher, there is at least a 10% chance that there will be a 4% loss of species.
- The model above is highly generalizable; as long as the impacts can be specified probabilistically as a function of equilibrium temperature increase, the same basic model structure can be used.
- It is fairly straightforward to modify such a model to use transient temperature increase (e.g., temperature increase at 2100). So far, however, there are no simple but robust probabilistic models of transient temperature increase in the literature.

## Conclusions

- There is not, and will not soon be, a single consensus PDF for the climate sensitivity.
- This is a general property of subjective probability estimates of uncertain parameters, including (for example) the rate of ocean heat uptake, the future strength of the carbon sink, etc.
- Accordingly, it will never be possible to say something like "the probability of temperature exceeding 2°C in 2100 is 5% if CO<sub>2</sub> emissions are held to 400 GtC over the 21st century" – the result of proper modeling, using multiple PDFs will always be a range, even if (as shown in the species loss model above) it is a small range.
- The design of policies which set risk targets must therefore not only specify an acceptable risk of exceeding some threshold, they must address how such a target will be set given the range of relevant input PDFs.

## References

- Andreanova, N. G. and M. E. Schlesinger (2001). "Objective estimation of the probability density function for climate sensitivity." *Journal of Geophysical Research* 106(D19): 22055-22011.
- Baer, P. (2005). *Justifying Climate Policy Choices: New Approaches to Uncertainty, Risk and Equity*. PhD Dissertation, University of California, Berkeley, CA.
- Boucher, O. and J. Haywood (2001). "On summing the components of radiative forcing of climate change." *Climate Dynamics* 18(3-4): 297-302.
- Clemen, R. T. and R. L. Winkler (1999). "Combining probability distributions from experts in risk analysis." *Risk Analysis* 19(2): 187-203.
- Ellenberg, D. (1981). "Risk, Ambiguity, and the Savage Acton's." *Quarterly Journal of Economics* 95(4): 643-669.
- Forest, C. E., P. H. Stone, A. P. Sokolov, M. R. Allen and M. D. Visbeck (2002). "Quantifying uncertainties in climate system properties with the use of recent climate observations." *Science* 296(5552): 1151-117.
- Frazer, D. J., B. B. Booth, J. A. Kettleborough, D. A. Starnworth, J. M. Gregory, M. Collins and M. R. Allen (2005). "Constraining climate forecasts: The role of prior assumptions." *Geophysical Research Letters* 32(9).
- Gregory, J. M., R. J. Stouffer, S. C. B. Rayner, P. A. Stott and N. A. Rayner (2002). "An observationally based estimate of the climate sensitivity." *Science* 296(5570): 91-95.
- Hansen, J. and M. Sato (2004). "Greenhouse gas growth rates." *Proceedings of the National Academy of Sciences of the United States of America* 101(46): 15919-15914.
- Knutti, O. W. (1998). "When is it appropriate to combine expert judgments?" *Climate Change* 39(2): 138-143.
- Knutti, R., F. Joos, S. A. Muler, O. W. Visbeck and T. F. Stocker (2005). "Quantifying uncertainties in climate system properties with the use of recent climate observations." *Science* 308(5715): 39-43.
- Knutti, R., T. F. Stocker, J. Joos and G. R. Potter (2002). "Constraints on radiative forcing and future climate change from observations and climate model emulations." *Nature* 416(6887): 719-723.
- Mastrandrea, M. D. and S. H. Schneider (2004). "Probabilistic integrated assessment of 'hazardous' climate change." *Science* 304(5670): 971-975.
- Meinshausen, M. (in Press). "On the Risk of Overheating 2°C." *International Journal of Climate Change*. Cambridge University Press, UK.
- Morgan, M. G. and M. Henrion (1990). *Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge, Cambridge University Press.
- Murphy, J. M., D. M. H. Stott, O. W. Visbeck, O. H. Barnett, G. S. Jones, M. J. Webb and M. Collins (2004). "Quantification of modelling uncertainties in a large ensemble of climate change simulations." *Nature* 430(7001): 768-772.
- Schneider, S. H. and M. D. Mastrandrea (2005). "Probabilistic assessment of 'hazardous' climate change and emissions pathways." *Proceedings of the National Academy of Sciences of the United States of America*. PNAS Early Edition September 6, 2005: 1-8. Available at <http://www.pnas.org/cgi/doi/10.1073/pnas.0508001102>
- Thomas, C. A., C. M. Allen, R. E. Green, M. Baklanov, L. L. Bledowski, V. C. Colglough, B. F. N. Erasmus, M. F. de Siquiera, A. Gargner, L. Henrich, S. H. Mullen, A. S. van den Broek, O. F. Murphy, J. M. Allen, M. A. O'Gara-Hartts, A. T. Peterson, O. L. Phillips and S. E. Villanov (2004). "Emission risk from climate change." *Science* 304(5670): 145-148.
- Wigley, M., C. Forest, J. Kelly, M. Bialski, D. Houghton, M. Meyer, R. Pinn, M. Sarin, A. Sokolov, P. Stone and K. Wang (2003). "Inventory analysis of climate change and policy responses." *Climate Change* 61(2): 295-303.
- Wigley, T. M. L. and S. C. B. Rayner (2001). "Interpretation of high projections for global-mean warming." *Science* 293(5529): 491-494.